HIGH SCHOOL STUDENTS' LEARNING DIFFICULTIES IN ELECTROCHEMISTRY: A MINI—REVIEW

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ABSTRACT

In this manuscript, we reviewed over 60 reports on the learning difficulties of electrochemistry in high-school education. In the first part of the review, we intend to introduce the learning difficulties that typically hamper in learning electrochemistry. Second, are those intending to introduce the apparent students' misconceptions in electrochemistry. Thirdly, the remedies that would improve the teaching-learning process of electrochemistry are highlighted. In order to attain this, the Web of Science search index was utilized to find out articles describing electrochemistry, learning difficulty, misconception, laboratory instruction, history, and philosophy of science terms (and phrases). The results revealed that there are over fifty most common students' misconceptions pertaining to the selected electrochemistry topics. Students' lack of ability to integrate big or core ideas with structure-property relationships; absence of teaching aids; misinterpretations of language in scientific contexts; frequent overloading of students' working memory; inability to represent chemical phenomena at the macroscopic, particulate, and symbolic levels; and teachers' and textbooks' made misconceptions are the main challenges that contribute to the students' learning difficulties in electrochemistry. As remedies, this paper identified the infusion of teaching methods such as laboratory-based instruction, the infusion of history, and philosophy of science in the electrochemistry lessons. Such teaching methods not just enhance the comprehension of electrochemistry concepts, but also improve students' attitudes towards the topic. The implications of the study to teachers and curriculum writers are discussed. *[African Journal of Chemical Education—AJCE 12(2), July 2022]*

INTRODUCTION

The history of electrochemistry is full of adventure and has played crucial role in advancing the understanding of chemistry and technology that shaped the production of industry and daily life in the 21st century. Alessandro Volta's invention of the first modern electrical battery in 1800—voltaic pile used to split water into hydrogen and oxygen in a process called electrolysis [1] is a cornerstone for the flourishment of electrochemistry. Little by little, many electrochemical concepts have been introduced in school chemistry curricula and many metals, such as Na, K, Al etc, were extracted from their compounds through electrolysis [2]. The ubiquitous nature of batteries in our day-to-day usage and the application of electrolysis for understanding corrosion, electroplating and extraction of metals lends electrochemistry to be widely studied at all levels of education elsewhere.

Fundamental topics of electrochemistry such as electrolytes, ions, electrolytic conduction, oxidation-reduction reactions, and electrochemical cells are introduced in secondary education [2-4]. However, electrochemistry is reported to be one of the difficult topics to both teachers and students (e.g. [3, 5-8, 9]. Some of the students' problems associated with learning electrochemistry topics are: (i) they get confused between the flow of electrons in metallic conductors and in the electrolytes; (ii) they cannot identify anode and cathode/negative and positive poles in the cell; (iii) their inability to explain the process happening at the anode and cathode; (iv) mixing up the oxidation and reduction processes that occur at the electrodes, and (v) they have difficulty in understanding an electrolyte concept [6]. Difficulties and misconceptions in electrochemistry is not only limited to students but also pre-service and in-service high school teachers [7-9]. To the best of our knowledge, review articles on the practices of teaching-learning of electrochemistry in lower and senior high-school levels are scant [3-4, 10].

This review is aimed at presenting the students' learning difficulties and possible remedies associated with teaching and learning of electrochemistry in high schools elsewhere. For this purpose two research questions had been set. These are:

1. What are the students' learning difficulties of electrochemistry in high schools?
2. How do students' learning difficulties related to electrochemistry are remedied in high-school classrooms?

METHODS

In the first part of this article, we aim to summarize reports that describe high-school students' learning difficulties of electrochemistry. In order to attain this, the Web of Science search index was used to source articles describing electrochemistry, misconceptions, learning difficulty, laboratory instruction, history, and philosophy of science terms (and phrases). Results obtained were filtered initially for high-school electrochemistry lesson, and then upon reading, filtered again to remove those that did not relate to high-school level electrochemistry topics. Cited and citing references of these articles were consulted to identify additional relevant material. Given the very extensive nature of literature on electrochemistry education, we do not consider having captured all of the reports on electrochemistry, but do consider that we have captured a suitable sample size to derive the evidence for the students' learning difficulties and the potential remedies. It is worth stating that while interesting literature on electrochemistry education relevant to modern teaching extends back to at least the 1800s; our survey starts in the early 1990s, as different teaching strategies emerged that made alternatives to better learn electrochemistry. In addition, where possible, we identified the type of electrochemistry topics (oxidation-reduction, galvanic, and electrolytic cells) and state that wherever possible when summarizing a report.

PART 1: A REVIEW OF LEARNING DIFFICULTIES

1.1. Learning difficulties in electrochemistry

Electrochemistry teaching and learning is one of the difficult lessons in high school chemistry and tertiary education elsewhere. Many chemical educators reported learning difficulties in understanding electrochemistry concepts which are prevalent in Africa [11]; Asia [5, 13, 14-15]; Europe [4, 16]; Australia [17]; and United States of America [18]. For instance, high school students, and teachers, come across problems in comprehending electric current, oxidation-reduction, electrolytes, galvanic cell [20] and electrolysis [7, 17, 19-20]. Students' limitations in understanding the 'particulate nature of matter' are reckoned the root cause for the challenges in learning chemistry concepts in general and electrochemistry in particular [21-22].. Thus, visual (what can be seen, touched and smell); sub-microscopic (atoms, molecules, ions and structures), and symbolic (representations of formulae, equations, mathematical expressions and graphs) should be employed for effective chemistry teaching [23-24]. In addition, students' limited knowledge of core or big ideas (e.g. see [25-26] in chemistry also creates difficulty to give scientific explanation and describe structure—property relationships [27-28].

[11] Reported the effect of using teaching models to minimize the known misconceptions in electrochemistry at South African university students. Their results revealed that students showed an improvement in understanding electrochemical cells at microscopic level along with the reduction of students' misconceptions. But students were found to entertain some of the misconceptions, after completing the lesson, such as: "current is a flow of electrons"; "ions will be able to conduct the electrons and complete the circuit"; "potassium sulphate has delocalized electrons and positive protons that move to the opposite electrodes when a current is applied"; and "anions produce electrons which conduct [electricity]" (p.107). Similar results were found in studies that take place at American students [18] and Australian students [17].

[5] Investigated Pakistani high school students' conceptual difficulties in the areas of redox reactions, galvanic and electrolytic cells. The results of their study suggested that students' correct response was only 67% of the concept-based test. The main factors that caused conceptual difficulties in comprehension were: (i) poor background knowledge, (ii) absence of teaching aids, and (iii) misinterpretation of everyday language into chemistry.

[12] Investigated high school students' (grade10-12) conceptual understanding of electrolyte concept in China. These authors found out that students faced difficulty in earning deep knowledge of electrolyte. [12] Studied 559 grade 10 to 12 students' conceptual understanding of electrolyte by using Rasch measurement instrument, which serve to measure both summative and diagnostic assessments of misconceptions in electrolyte concepts at two cities of China. The results indicated that students' conceptual understanding was enhanced with increasing grade levels while each of the different grade levels were found to hold misconceptions. [12] Reported the 10th grade students' understanding of the concept of *electrolyte* in China high school using a phenomenography method by interviewing eight students to qualitatively assess their level of understanding. Their research findings revealed that electrolyte concept was found to be difficult to be understood by students.

[13, 15] examined Malaysian high school students' conceptual understanding of electrolysis. In a study of 330 Malaysian high school students, [13] reported a two-tier 17 item multiple choice Electrolysis Diagnostic Instrument (EDI) to investigate students' understanding of basic electrolysis concept. She identified more than twenty misconceptions pertaining to different electrolysis concepts such as: (i) the nature and reaction of the electrodes; (ii) the migration of ions; (iii) the preferential discharge of ions; (iv) the products of electrolysis; and (v) changes in the concentration and color of the electrolyte. According to [15] high school students in Malaysia face difficulties in explaining basic electrolysis concepts and lacking confidence in correctly answering test questions. They recommended that teachers "should help select the teaching materials such as

the appropriate use of models, illustrations and definitions of new terminology to help students learn chemistry concepts more effectively" (p.1341).

[14] Investigated 244 Indonesian and 189 Japanese public senior high school students' conception of electrochemical concepts (e.g. electrolysis, electricity flow, the voltaic cell and the electrode reactions). The result revealed that both samples exhibited difficulty in understanding of the concepts and held misconceptions.

A related study in German upper secondary schools investigated the learning difficulty of students [16]. The study focused on four areas, namely, electrolytes; transport of electric charges in electrolyte solutions; the anode and the cathode; and the minus and plus poles. Students' reasoning was based on the misconceptions: "the electric current produces ions"; "electrons migrate through the solution from one electrode to the other"; "the cathode is always the minus pole, the anode the plus pole" and "the plus and minus poles carries charges" [16].

Student teachers showed teaching difficulty of electrolysis whereby they were unable to explain what an electrolysis is and why the electrochemical phenomena in electrolysis process has happened as well as they did not ponder the actual electrolysis mechanisms to their students [7]. Their results revealed that only two students were able to explain electrolysis as a process where an electric current drives the reaction to a non-spontaneous direction. Some student teachers also hold misconceptions in electrolysis. All the aforementioned difficulties and misconceptions related to students and teachers, necessitates remedies that could led to an effective classroom discourse and robust understanding of electrochemistry.

PART 2: MISCONCEPTIONS IN ELECTROCHEMISTRY

Misconception is referred to as learners' scientific views and beliefs that are inconsistent with the commonly accepted views of the scientific community [8, 29-31].Science educators also coined various terms for misconceptions such as alternative conceptions [10], children's science [30-31], alternative frameworks [12, 17], and conceptual or propositional knowledge [29] to describe students' understanding that is in conflict with the scientific view. An awareness of the misconceptions in electrochemistry would guide high-school teachers, textbook writers, curriculum developers and policy makers so as to design and execute an effective instruction, assessment and implementation of a curriculum so that students' scientific conception would be in harmony with the consensus of the scientific community.

As Piaget (Cited in [26], p.6059) contended, when there is inconsistency in the understanding of a new concept and our pre-existing knowledge, the conceptual schema of the learner tends to modify in a way that fits the 'new sensory data'. Thus, the students can have different views on a particular concept to accept it as correct or incorrect since they are in a position to compile and integrate knowledge under a constructivist paradigm. The chance of creating their own wildly accepted perspectives to understand chemical phenomena is the cause for holding misconceptions

[26]. The misconceptions research in electrochemistry is well documented in various studies [8, 14-16, 18, 21, 32-37]. However, several chemical educators strongly criticized that many misconception research has paid little attention on the possible sources of the learning difficulties and misconceptions. [38, p.230] clearly argued that "Chemistry educators who strongly emphasized that developing effective instructional approaches to overcome misconceptions requires identifying and considering the underlying sources of these misconceptions, rather than merely listing them.

Creative exercises that promote meaningful conceptual links between prior knowledge and new knowledge, pretest and posttest exams, and interviews and students' reflection about their own learning and small group discussions are used to trace misconceptions held by students in electrochemistry. Integrated concept mapping and visual animation is also important in identifying students' misconceptions and attracting their interest and enhancing the performance of learning in electrochemistry [39]. The possible origins of misconceptions are: (1) inadequate prerequisite knowledge; (2) frequent overloading of students' working memory; inability to think about the same chemical processes at the macroscopic, particulate and symbolic levels; misinterpretation of everyday language in chemical contexts; (3) the use of concepts and algorithms in a rote fashion without any attempt to understand fully and analyze the problem; (4) Teachers and textbook-derived misconceptions ; and (5) the format and order used in chemistry textbooks [3, 18, 29, 40]. These learning difficulties and misconceptions necessitate an effective instructional approaches and strategies such as conceptual change approach [33, 41].

Conceptual change instruction is referred to as a teaching method that requires restructuring of learners' existing conceptual frameworks to a much more organized scientific knowledge structure [30]. It should create opportunity for learners' dissatisfaction with their misconceptions and the new conception should be intelligible (understandable), plausible (believable) and fruitful (worthwhile) so as to extinguish their misconceptions and for a sound understanding to occur [10, 42]. The strategies that are very helpful for cognitive restructuring to be feasible includes: providing opportunities to exchange ideas in the classroom and encouraging group discussions, eliciting students' experiences, guiding students to reflect their own learning and giving freedom to take responsibility to their own learning as well as make meaning to their experiences [10, 30]. However, students' misconceptions in electrochemistry could not be fully avoided due to its nature of resistance to change [31]. While students' active engagement in scientific activities is a prerequisite for cognitive restructuring to occur, learning science involves a complex interplay between personal experience, language, and socialization.

Previously, the conceptual understanding of high school students (grades 9-12) has been studied and an overwhelming number of misconceptions on oxidation-reduction and electrochemistry were identified [4, 6, 10, 14, 16, 20, 31, 35, 42-46]. The most common misconceptions on oxidation-reduction and electrochemistry were grouped into five subcategories: (1) Electric circuits; (2) Oxidation-Reduction; (3) Galvanic/Electrochemical cells; (4) Electrolytic cells, and (5) Electrolytes are indicated in Table 1-5 below.

2.1 Electric circuits

The use of different conventions to explain electric current, “flow of electrons” model and “flow of electric charges” model in chemistry and physics subjects respectively, leads students to misinterpret electric current as it is generated by the movement of (only) electrons in chemistry and the flow of positive charges in physics subjects, as indicated in conceptions 1, 4, 5, 8 and 9 in Table 1. Actually, the two models were used to describe electric current, and electricity in general, contains similar concepts—the flow of electrons constitute current in chemistry and the flow of electric charges which is basically the electrons that have negative charges in physics. Due to the students’ application of different models, students compartmentalized chemistry and physics and view these subjects as unrelated and different disciplines.

Teachers must show the interrelatedness of the electricity concepts in chemistry and physics and the importance of the flow of positive and negative ions or charges (in solutions) and electrons (in the external wire and in metallic conductors) in generating electric current should be given witty explanations to the students. However, a simplified use of “flow of charge” model has limitations to fully explain the metallic conduction process.

Table 1 Misconception in Electric Circuits

Electric circuits
1. Electric current only occurs by movement of electrons
2. Electrons enter the electrolyte at the cathode, move through the electrolyte and emerge at the anode to complete the circuit
3. The salt bridge supplies the electrons to complete the circuit and assists the flow of current (electrons) because positive ions in the bridge attract electrons from one half-cell to another
4. Only negatively charged ions constitutes the flow of current in the electrolyte and the salt bridge
5. Protons and electrons flow in an opposite direction to constitute an electric current
6. Electrons can flow through aqueous solutions without assistance from the ions
7. Electrons move in solution by being "carried" by the ion
8. Protons flow in metallic conductors
9. Electricity in chemistry and physics is different because the current flows in opposite directions
10. The current flows because there is a difference in charge at the anode and cathode.

In conceptions 2, 3, and 6, students misinterpret the statement "the salt bridge serves to "complete" the circuit, allowing electrical current to flow" as if electrons pass through the salt bridge and solution in order for the cell to generate constant electricity. The effects of language barrier, everyday language with dual meanings, in scientific contexts hinder students' chemistry learning in such a way that the most frequently used meaning persists. The teacher should scaffold students' developing competence to interrelate the macroscopic, sub-microscopic and symbolic representations of chemical concepts and this is an effective instructional strategy to extinguish misconceptions and for successful learning to occur [24, 47-48]. Similarly, the use of the statement "positive and negative ions carry charges" or "ions are charge carriers" confuses students' as the everyday language "carry" gives opportunity to devise their own way to understand electrons could be carried by the ions and flows in either direction into the electrodes, conception 7. Thus, teachers and textbook writers should carefully consider the language barrier in chemistry learning and be explicit in defining chemical concepts. Students' lack of understanding of the relative tendency of electrodes to undergo oxidation and reduction, leads to believe that the difference in charges between the electrodes is the driving force for an electric current to flow in the external wire, conception 10.

2.2 Oxidation-reduction

The use of multiple models to define oxidation and reduction processes: addition of oxygen or removal of oxygen; addition of hydrogen or removal of hydrogen; transfer of electrons from one substance to another, and the change in oxidation state is misleading and confusing [3, 10]. For example, in a combustion reaction $C+O_2 \rightarrow CO_2$, students regard this process only as an oxidation reaction since oxygen has been added, conception 17. When students use the oxygen addition or removal and hydrogen addition or removal models and as such try to apply it for all chemical equations, they will fail to identify the oxidation and reduction half-cells and the chemical changes that occur due to these changes, conceptions 11, 18 and 19.

Teachers should be consistent with their models while defining oxidation and reduction concepts and should encourage students to use the ‘change in oxidation state model which is more realistic to define all redox equations certainly [49].

Table 2 Misconceptions in Oxidation-Reduction

Oxidation-reduction
11. Metal rods only act as an electron carrier during redox reactions and there will be no change in the electrodes physical structure
12. Inert electrodes can be oxidized or reduced
13. The oxidation state of an element is the same as the charge of the monatomic ion of that element
14. Oxidation states or numbers can be assigned to polyatomic molecules and/or polyatomic ions
15. The charge of a polyatomic species indicates the oxidation states of the molecule or ion
16. In an equation, changes in the charges of the polyatomic species can be used to determine the numbers of electrons removed from, or gained by, reacting species
17. Oxidation and reduction processes can occur independently
18. When electrons are transferred from copper to silver, the charges of these species do not change
19. In all chemical equations the “addition” and ”removal” of oxygen and hydrogen can be used to identify oxidation and reduction
20. No reaction will occur in inert electrodes

While assigning the oxidation states of a substance is important in the identification of oxidation and reduction reactions, students’ have difficulty in giving correct oxidation states for an element and polyatomic ions—assigning an oxidation state of +2 for Zn metal and in $Cr_2O_7^{2-}$ ion they assign an oxidation state of -2 for Cr but in reality, it is +6. This is indicated in students' conceptions 13 and 15. They wrongly thought that the oxidation state of polyatomic molecules or ions can be assigned, conception 14 and is the same as its charge, conception15. In a chemical equation that contains CO_3^{2-} ion in the reactant side and CO_2 in the product side, students assign an oxidation state of -2 for CO_3^{2-} and 0 to CO_2 molecule and thought the process is an oxidation reaction because the oxidation state has changed from -2 to 0, conceptions 14, 15 and 16.

In conceptions 12 and 20, students literally translate the word "inert" as it means one that does not react. However, inert electrodes conduct electricity and reaction can occur at this electrode even though the inert electrode itself does not react. The everyday language in chemical context misled students to think either inert electrodes could be reduced and oxidized, or they will not react at all. Teachers and textbook writers should critically select an appropriate word that does not confuse students' thinking towards chemistry learning.

2.3 Galvanic/Electrochemical cells

Labeling anode and cathode as negative and positive charges exacerbates students' understanding on the mechanism of electron flow along the external wire and the transport of anions and cations into the electrolyte solutions and salt bridge. Students who hold a common belief that anode is negatively charged (with surplus electrons) could not explain how a drift of anions come to the negatively charged anode electrode, conception 21. In the same vein, students who believe that anode is a positively charged species were unable to explain the flow of electrons from the anode to the cathode (with electron deficiency) to undergo a reduction reaction, conception 22.

Students showed lack of understanding about the functions of the salt bridge in electrochemical cells, conceptions 23, 33, 35 and 38. The statements used to indicated the role of salt bridge "the salt bridge complete the circuit, allowing the electrical current to flow" and electrolytes and salt bridge serve to "maintain the electrical neutrality of the circuit" are misunderstood by the students and believe that the salt bridge is helpful to transport both positively charged and negatively charged ions as well as electrons from one electrode to the other so that the development of positive and negative charges at the electrodes will be restricted. The common words "complete" and "neutral" are misrepresented in the scientific context and due to this language barrier, students could not understand what the actual function of salt bridge is.

Table 3 Misconceptions in Galvanic/Electrochemical cells

Galvanic/Electrochemical cells
21. The anode is a negative electrode and because of this it attracts cations and the cathode is positively charged and because of this it attracts anions
22. The anode is positively charged because it has lost electrons while the cathode is negatively charged because it has gained electrons
23. No transfer of salt-generated ions from one to the other cell
24. The identity of anode and cathode depends on the physical placement of the half-cells
25. In an electrochemical cells oxidation occurs at anode and reduction occurs at the cathode, while in electrolytic cells oxidation occurs at the cathode and reduction occurs at the anode

26. No reactions will occur if inert electrodes are used
27. In electrochemical cells, as the attraction forces between anions and cations affects ions velocity to electrodes, different potentials are read when different solutions are used in the cells
28. Protons and electrons flowing in opposite directions cause a potential difference between the two ends of the wire
29. There is high electron concentration at the anode
30. In standard reduction potential tables the species with the highest E^o value is the anode
31. The number of neutral atoms increases in the anode, while it decreases in the cathode
32. The number of metal cations increases in the reduction half cell, while it decreases in the oxidation half cell
33. Salt-generated cations transferred from the reduction to the oxidation half cell
34. The anions and cations move until their concentrations in both half-cells are equal.
35. Cations in the salt bridge and the electrolyte accept electrons and transfer them from the cathode to the anode.
36. The cathode is always the minus pole, the anode the plus pole
37. The anode electrode mass increases over time
38. The positively charged ions migrate toward the anode electrode, whereas the negatively charged ions migrate towards the cathode electrode over the salt bridge.

In order to minimize this confusion, simple paper-based and low-cost galvanic cells are very helpful [50-53]. This is since “the models of galvanic cells provided students a chance to access the microscopic level to direct perception” [20, p.403].

Some students have difficulty in identifying the anode and cathode electrodes, conceptions 24 and 36. Labeling of anode and cathode electrodes as either negative and positive is highly dependent on the relative tendency of the electrodes to lose or gain electrons but this does not necessarily mean that the electrodes possess absolute negative or positive charges. Thus, the identification of anode and cathode has nothing to do with their physical placement, even though some students believe it so, conception 24. The assignment of positive and negative charge to the anode and cathode is dependent on the type of cell, whether galvanic or electrolytic cell, since in galvanic cells the lost electrons in the anode did not need any additional electrical energy to transport them to the cathode but in electrolytic cell, a direct current is needed to transport the lost electrons in the anode and thus the anode should be connected to the positive terminal of the battery.

Lack of this basic understanding of labeling anode and cathode as either positive or negative, creates confusion among some students to have conception that anode is always a negative pole while cathode is positive pole, conception 36. Most students' inability to distinguish between electrochemical and electrolytic cells, creates learning difficulties in understanding the redox reactions that occur at these cells. Furthermore, teachers often used the word "reversed" to describe the processes in electrolytic cells compared to galvanic cell. This led students to a wrong conception that oxidation occurs at the cathode while reduction occurs at the anode in electrolytic cell, conception 25. Teachers need to critically scrutinize what appropriate words, that did not interfere in students' chemistry learning, should be used in order to describe electrochemical and electrolytic cell concepts. Another interesting common belief of students on the function of inert electrodes is that no reaction will occur at inert electrodes, conception 26. Misinterpretation of the word “inert” in their everyday language prevents students to think that there is a reaction in the inert electrodes even though they did not participate in the reaction. Still teachers should be careful in using everyday languages in the scientific contexts in chemistry teaching.

Some students believed that the type of solutions used in galvanic cell affects the amount of cell potential generated due to redox reactions, conception 27. As long as the solutions used in the electrodes did not interfere in the redox reactions, every galvanic cell has a characteristic cell voltage irrespective of the types of solutions with known concentrations are used. This is students’ naïve belief that should be corrected by engaging students in group discussions that promote critical thinking skills.

Students’ Conception 28 arises from the compartmentalization of knowledge in chemistry and physics. (See conception 5 above).

Some students have difficulties in understanding how galvanic cell performs and they happened to misrepresent the concept of electrical neutrality in a cell, conceptions 29, 31, 32, and 34. In order to remedy these conceptions, teachers should use small-scale experiments along with model kits via inquiry-based laboratory instruction that could activate students’ cognition and attract their interest to learn galvanic cells in a particulate level effectively [20].

Conception 30 is erroneous information that is held by students through mere rote memorization for the purpose of passing exams instead of making meaning to it. [10] Described such kinds of learning as "the information is neither meaningful nor understandable to the student and has been rote learned in order to answer test questions" (p.86).

Students who lack the ability to understand the phenomena at a particulate/microscopic level showed a weak understanding in describing what is happening in the amount of mass changes in electrodes of a galvanic cell, conception 37.

The use of computer animations and animated concept mapping [39], small scale experiments that encourages students' visualization ability [20, 50-53], and chemistry triplet learning [24, 40-48] are very helpful for creating sound understanding of electrochemical concepts at the particulate, visual and symbolic levels.

2.4. Electrolytic cells

Students' inability to explain the electrolytic process as a process that consumes electrical energy to effect a chemical change led students to hold a number of misconceptions such as the oxidation and reduction half-cell reactions will not be affected when the applied voltage is attached at either side of the electrodes, conceptions 39, 43 & 44.

Table 4 Misconceptions in Electrolytic Cells

Electrolytic cells
39. In electrolytic cells the polarity of the terminals of the applied voltage has no effect on the site of the anode and cathode
40. Water does not react during the electrolysis of an aqueous solution
41. The same products are produced in both aqueous and molten situations of salt electrolysis
42. There is no association between the calculated e.m.f of an electrolytic cell and the magnitude of the applied voltage
43. In electrolytic cells with identical electrodes connected to the battery the same reactions will occur at each electrode
44. It is not important which sides of the battery are connected to the electrodes as the same reactions occur at the electrodes
45. The predicted e.m.f. for an electrolytic cell may be positive
46. Electrolytes are decomposed by electric current.
47. No electrolytic anions transfer from one to the other half-cell
48. No reactions will occur at the surface of inert electrodes
49. Processes in electrolytic cells are the reverse of those in electrochemical cells

The students' common belief that the site of the applied voltage does not affect the redox process arouse from the confusion between the chemical changes of anode and cathode electrodes and due to the limitation in understanding the mechanism of the flow of electrons in the external wire and the transport of charges into the electrolyte solution. Since electrolytic process is a non-spontaneous process, the anode should be connected to the positive terminal of the battery so that the lost electrons in the anode electrode will be transported to the cathode electrode, which is connected to the negative terminal of the applied voltage or battery, through the external wire. However, the change in the site of connection of the electrodes with the battery will also change the types of products obtained at each electrode. This problem can be remedied by making use of small-scale electrolysis experiments as they could give opportunity for students to realize what is happening at microscopic, particulate, or sub-microscopic and symbolic levels [55-57]. In addition, small group discussions among students will enhance their understanding about the electrolytic concepts and the principles associated with it. Conception 45 relate to the confusion of the principles of electrolytic cell. Since the function of the electrolytic process is not to generate electricity, the e.m.f. value will not be positive as the process is non-spontaneous—it would rather need an external direct current source to effect the chemical change.

Students' inability to describe an oxidation-reduction reaction led them to think that the applied voltage that is needed to drive a redox reaction in electrolytic cell is independent of the calculated cell potential, conception 42. The voltage required to cause electrolysis depends on the specific half-reactions, i.e. the applied voltage should be greater than the calculated e.m.f in order to force the electrons to flow in the opposite direction. This is similar to conceptions 39 and 44.

Conceptions 40 and 41 relates to the lack of understanding of the discharging and oxidation and reduction processes of the molecules and ions. The reason for students' misconception might be associated with their incapability to provide the dissolution equation of salt in water and inability to understand the ions present in the molten salt. Another reason might be the lack of understanding of the selective discharging of the ions/or molecules at either of the electrodes. In electrolysis of water in aqueous solution, the metal cations of the salt will not be discharged as water molecules require lower voltage to do so.

Students' naïve belief that an electric current helps to decompose the ions in an electrolyte solution, conception 46, arouse from misinterpretation of electrolysis process as the decomposing ions in the electrolyte instead of the splitting of a compound into its corresponding elements.

Conception 47 relates the poor understanding of the flow current in an electrolytic cell. Some students believe that in electrolytes electrons are carried by the ions and moved to the electrodes while other students do not think anions will be transferred from one to another cell. This misconception is due to incapability to explain how electrical neutrality of a cell is maintained.

The functions of inert electrodes create some sort of confusion to some students, conception 48, and take the literal meaning of "inert" as it does not react. The difference between electrochemical and electrolytic cells is misunderstood by students, conception 49. Teachers and textbooks' statements "electrolytic cell processes are the reverse of electrochemical processes" is misunderstood by students as each and every process of the electrolytic cell is the direct opposite of electrochemical cells. Simply taking the common meaning "reverse" in everyday language, some students believed that oxidation occurs at the cathode while reduction occurs at the anode in electrolytic cells. Another student might believe that before writing a net cell reaction, the half-cell reaction equations must be exchanged, etc.

2.5. Electrolytes

Conceptions 50 and 51 indicates students' lack of understanding of the electric current flow model in chemistry and physics—compartmentalization of knowledge. Some students' thought that strong ionic boding occurs in solutions, conceptions 52, 53 and 54. Other students have difficulty in distinguishing between ionization and dissolution processes, conception 55.

Table 5 Misconceptions in Electrolytes

Electrolytes
50. Protons flow in electrolytes (regardless of whether the solution is acidic, basic or neutral)
51. Protons and electrons flow in opposite directions in an electrolyte
52. Aqueous solution contains sodium chloride molecules, in which sodium and chlorine molecules are bound together in 1:1 proportion
53. Cations and anions are attached or bonded together as ion pairs in water
54. Ionization and dissolution are the same process
55. Electrolyte solution are not conductive

PART 3: STRATEGIES FOR EFFECTIVE ELECTROCHEMISTRY LEARNING

3.1. Laboratory instruction for teaching and learning electrochemistry

Table 6 shows a summary of laboratory instruction approaches and strategies on effective electrochemistry teaching and learning at high school level. In a recent review study, [4] investigated high school and university students' learning challenges and effective teaching strategies and approaches intended for enhancing conceptual understanding and increasing positive attitudes towards electrochemistry. The results revealed that inquiry-based 5E instruction model and projected-based learning activities indicated a profound impact in: (i) the comprehension of electrochemistry concepts, (ii) for holding positive attitudes in chemistry learning and (iii) development of communication skills. This is consistent with [67] commentary paper on his 32 years' experience in using laboratory instruction for teaching chemistry. During his 2010 ACS "Award for Achievement in Research for the Teaching and Learning of Chemistry", he explicitly addressed the impacts of inquiry-based laboratory teaching as an effective instruction for students' conceptual understanding and increasing their attitudes. [59] Investigated the effect of five inquiry-based laboratory activities aimed at improving 62 Turkish high school students' achievement and positive attitudes in electrochemistry learning.

Their findings strongly suggested that inquiry-based instruction has greatly supported students' comprehension of electrochemistry concepts on: (1) flow of electrons, (2) function of salt bridge, (3) identification of anode and cathode and (4) earning deep and robust understanding of electrochemical cells. In addition, students were found to hold positive attitude towards chemistry and laboratory work. Several similar studies have also been reported on the merits of inquiry-based laboratory instruction [20, 59-54].

A study which is conducted on 50 form four (equivalent to grade 9) high school students in Malaysia assessed the effectiveness of integrated STEM lab-activities in facilitating students' understanding of electrolysis using two-tier 17-items Electrolysis Diagnostic Instrument (EDI) and interviewing students [67]. These researchers found out that students' understanding of electrolysis has been improved with 33.6% of the variance in the pre-and post-test explained by the treatment.

Several small-scale and low-cost experiments for successful teachings of electrolysis to high school students are well established [54-57] While small-scale and low-cost electrochemistry experiments are important in minimizing students' conceptual difficulties, yet the use of molecular animations and inexpensive, portable, reproducible, and flexible model kits via 5E inquiry learning approach has synergetic effect that leads to an effective electrochemistry instruction [20].

Some studies are reported on paper-based galvanic cells which have high impact in teaching electrochemistry in high school [50-53].

Table 6 Summary of Laboratory Instruction Strategies and Proposals for Effective Teaching and Learning in Electrochemistry at High Schools

Main Features	Author (s) and Year of Publication
A Small-Scale and Low-Cost Apparatus for the Electrolysis of water	[54]
Small-Scale and Low-Cost Galvanic Cells	[64]
A Model Approach to the Electrochemical Cell: An Inquiry Activity	[40]

Hydrogen and fuel cell educational activities in Turkey	[65]
Microscale Electrolysis Using Coin-Type Lithium Batteries and Filter Paper	[55]
Electrolysis of Water in the Secondary School Science Laboratory with Inexpensive Microfluidics	[56]
Grade 12 students' conceptual understanding and mental models of galvanic cells before and after learning by using small-scale experiments in conjunction with a model kit	[20]
An Easy-To-Assemble Three-Part Galvanic Cell	[52]
A microfluidic galvanic cell on a single layer of paper	[53]
STEM teaching in a chemistry laboratory "How to build a simple battery in the laboratory"	[66]
Electrochemistry with Simple Materials to Create Designs and Write Messages	[57]
Teaching and Learning Electrochemistry	[4]
Integrated STEM-lab activities in improving secondary school Students' understanding of electrolysis	[67]

3.2. History and philosophy of science

The use of historical perspectives of science as instructional method for teaching introductory high school chemistry courses are reported by many chemistry educators [1, 48, 68-72].

[25] Pointed that history of science “helps to recognize struggles in the understanding of central concepts and big ideas in the discipline, many of them similar to the challenges that students face in our classrooms” (p.837). Replication of 19th century electrochemistry experiments such as Alessandro Volta’s battery and reconstructing it played crucial role to recover knowledge and to advance electrochemistry knowledge in the current science education [1]. Chang concluded that historical experiments, complementary experiments, are very intriguing for students and teachers to develop ‘a genuine experience of open-ended scientific inquiry’ and learn the essence of original research work by reconstructing earlier experiments (p.337). [70] reported reconstructing of an iconic experiment on electrolysis of water to teach pre-service teachers in a history of science course at Norwegian University of Science and Technology in Norway using water-splitting apparatus and voltaic pile— which are part of historical collections of the university. Water-splitting apparatus and voltaic pile are featured in the 19th and 20th century physics and chemistry textbooks and high school teaching classrooms. Authors built a replica of voltaic pile. Results of these authors showed that students appreciated the electrochemistry experiment. But authors also found a peculiar result about the ratio of hydrogen to oxygen which was not exactly 2:1 as suggested in written sources even though authors enjoyed their experience a lot.

It seems apparent that historical experiments are very helpful to the understanding of scientific concepts as students and teachers will get opportunities to ask critical questions such as: Why do we believe what scientists said then? Why is it happened so? What are the reasons for such findings? [25] Contended that historical perspective of science teaching aids to open our eyes to “the underlying themes, essential questions, scales of analysis, conceptual dimensions, contextual issues, and philosophical considerations that have emerged from the work of chemists throughout the ages”.

[72] Investigated grade 11 high school students’ conceptual mastery of energy in physics course by making use of HPS. Researchers designed a teaching strategy based on HPS approach using five teaching activities: (i) study and reproduction of Joule's paddle-wheel experiment, (ii) introduction of Rankine's definition, (iii) study of a historical text of Joule, (iv) use of an “ID card of energy,” and (v) early introduction and multiple application of the principle of energy conservation. The results showed that the teaching design is promising, and students’ conceptual comprehension of energy is enhanced. Electrochemistry teaching can also be adapted using this pedagogy as it deals with the electrochemical transformation of energy but with a different teaching context.

Some researchers reported the impact of incorporation of historical experiments in high school chemistry textbooks’ for effective chemistry teaching [68-69] In his study, Lin suggested that textbooks should emphasize students’ qualitative conceptual understanding of chemistry concepts than algorithmic mathematical problems, as students can solve it correctly but with little understanding of concepts [68]. His findings indicated that experimental students were able to comprehend “atmospheric pressure” and “atoms” along with minimizing misconceptions. He recommended that “debating” and “role-playing” could be used to integrate different historical chemistry topics into classroom teaching. [69] Examined French and Tunisian high school chemistry textbooks' historical implications for effective Daniel cell and electrochemistry teaching. The results showed that a Daniel cell containing two compartments separated by a salt bridge is found to be suitable to teach oxidation-reduction concept. However, the Daniel cell teaching model creates learning difficulty of ionic conduction. Authors suggested that identifying students' prior conceptions and chemical thinking about electrochemical cells using diagnostic tests could help to address electrochemistry concepts.

CONCLUSIONS

In this review, authors mainly focused on examining the high-school students' learning difficulties in learning electrochemistry elsewhere and what instructional strategies aid to attain the students' learning outcomes. To attain this purpose, selection criteria of articles and the methods of analysis for this review was established.

The results of this study revealed that electrochemistry is one the difficult topics for both students and teachers—faced challenges to comprehend concepts such as redox reactions, electric current, electrolytic cell, electrolysis, electrolyte and galvanic cells and entertain misconceptions in these topics. Students' lack of ability to integrate big or core ideas using structure-property relationships; poor background knowledge; absence of teaching aids; misinterpretations of language in scientific contexts; frequent overloading of students' working memory; inability to represent chemical phenomena at the macroscopic, particulate and symbolic levels; the use of concepts and algorithms in a rote fashion without any attempt to understand fully and analyze the problem, and teachers' and textbooks' made misconceptions are the main factors for students' recurrent challenges in studying electrochemistry.

The findings of this review have implications for future research and for planning instructions of electrochemistry in high school classrooms. Experiences of high school students towards electrochemistry teaching around the world revealed that a laboratory work instruction, history and philosophy of science greatly enhanced comprehension of concepts as well as improved students' attitudes. The findings on misconceptions and learning difficulties of oxidation-reduction and electrochemistry are more likely to help teachers and curriculum developers to improve students' conceptual understanding and attract their interest towards chemistry learning.

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